

The University of Chicago

A QUANTITATIVE INVESTIGATION
OF SPECTRAL LINE INTENSITIES
IN O- AND B-TYPE STARS

A DISSERTATION SUBMITTED TO THE
FACULTY OF THE DIVISION OF THE
PHYSICAL SCIENCES IN CANDIDACY FOR
THE DEGREE OF DOCTOR OF PHILOSOPHY

DEPARTMENT OF ASTRONOMY AND ASTROPHYSICS

1936

By
PAUL RUDNICK

Private Edition, Distributed by
THE UNIVERSITY OF CHICAGO LIBRARIES
CHICAGO, ILLINOIS

Reprinted from
THE ASTROPHYSICAL JOURNAL
Vol. 83, No. 5, June 1936

The University of Chicago

A QUANTITATIVE INVESTIGATION
OF SPECTRAL LINE INTENSITIES
IN O- AND B-TYPE STARS

A DISSERTATION SUBMITTED TO THE
FACULTY OF THE DIVISION OF THE
PHYSICAL SCIENCES IN CANDIDACY FOR
THE DEGREE OF DOCTOR OF PHILOSOPHY

DEPARTMENT OF ASTRONOMY AND ASTROPHYSICS

1936

By
PAUL RUDNICK

Private Edition, Distributed by
THE UNIVERSITY OF CHICAGO LIBRARIES
CHICAGO, ILLINOIS

Reprinted from
THE ASTROPHYSICAL JOURNAL
Vol. 83, No. 5, June 1936



A QUANTITATIVE INVESTIGATION OF SPECTRAL LINE INTENSITIES IN O- AND B-TYPE STARS*

PAUL RUDNICK

ABSTRACT

Measured total absorptions are given for the stronger spectral lines in seventy stars of Harvard types O and B. The intensities were measured on one-prism spectrograms with a photoelectric microphotometer, using a square diaphragm large enough to include the entire line; in this manner some lines could be measured that were too faint and broad to be seen.

Behavior of H lines.—The behavior of hydrogen intensities with spectral type is shown, first for all of the stars measured, and then for Struve's giant and dwarf groups. The marked enhancement of hydrogen in the dwarfs is confirmed. It is shown that there is no systematic difference in the hydrogen intensities between diffuse-line and sharp-line stars.

Behavior of He I lines.—The lines of the triplet system of He I are shown to fade out more slowly than the singlet lines on the high-temperature side of maximum; no appreciable difference is found between the systems on the low-temperature side of maximum. Intensities of all He I lines, when plotted against spectral type, show a much more definite maximum in dwarfs than in giants. The suspected shift of maximum from B₂ in dwarfs to B₁ in giants is confirmed. Differences are shown to exist between giants and dwarfs in the behavior of the singlet-to-triplet ratio. The enhancement of He I lines in dwarfs in types earlier than B₃ is confirmed. At type B₂, the strongest lines measured in both singlet and triplet systems are about 50 per cent strengthened in dwarfs as compared with giants. At B₂, the triplet λ 4472 is about 50 per cent stronger than the singlet λ 4388. It is shown that the differences between singlets and triplets in giants and dwarfs cannot be due entirely to gradient effect.

The position of maximum intensity of the helium lines is found to be B₂ for stars with sharp lines; for wide-line stars it is shifted to B₄.

Behavior of lines of other elements.—The behavior with spectral type is given for lines of the following elements: Si II, Si III, Si IV, He II, N II, N III, C II, and Mg II. The strengthening of λ 4481 of Mg II in giants of type B₅ and later is found to be about 40 per cent. Si II, Si III, Si IV, N II, and N III are all found to have about twice the maximum intensity in giants that they attain in dwarfs. Almost all of these elements are found to show no appreciable difference in behavior between wide-line and sharp-line stars.

I. INTRODUCTION AND OBSERVATIONAL MATERIAL

In order to discuss on a uniform basis the intensities of spectral lines of important elements, with various amounts of broadening or with appreciable separation in the spectrum, it seemed worth while

* [This article was received by the editors a few days later than the papers by E. G. Williams printed in the May issue of this *Journal*. Although there is a certain amount of duplication in these two independent investigations, the results are believed to be of sufficient importance to justify the publication of both. No attempt has been made to co-ordinate the results, but the agreement in all the major conclusions is very satisfactory.—THE EDITORS.]

to secure a consistent set of measured total absorptions of all lines strong enough to be well measurable, for a large number of early-type stars. Some work of this nature has already been done by E. G. Williams,¹ who made photometric determinations of line intensities in groups of giant and dwarf O- and B-type stars. Struve^{2, 3} has made studies of larger groups of the same types, based mainly on eye estimates of the relative strengths of lines, with special reference to the behavior of *He* I and *O* II. Miss Payne⁴ has investigated the behavior, with changing spectral type and with luminosity, of the spectra of numerous atoms; she has worked both with measured line profiles and with estimated data. Elvey has studied profiles of lines of *H*,⁵ *He* I,⁶ *Si* III,⁷ and *Mg* II⁸ in the early-type stars.

In the present work, photometric measures of line intensities were made, by the method described below, for the stronger lines of seventy stars of Harvard spectral types Oe to B9. On the basis of the data obtained from these measures, discussions are given of (1) anomalies in the behavior of neutral helium and (2) certain differences in behavior between spectra having sharp and diffuse lines.

The observational material includes eighty-two spectrograms of seventy stars. All but two of the plates were taken with the one-prism dispersion of the Bruce spectrograph (26 Å/mm at *Hγ*); the other two were taken with three prisms (8 Å/mm at *Hγ*). Table I gives for each star the following data, obtained almost entirely from Schlesinger's *Catalogue of Bright Stars*: BS number; name of star; equatorial co-ordinates for 1900.0; apparent magnitude; Harvard spectral type; Victoria spectral type;⁹ classification (to be discussed hereinafter) as giant or dwarf and as to line-width class; number of spectra measured.

¹ *Pub. A.S.P.*, **46**, 292, 1934.

² *Ap. J.*, **74**, 225, 1931.

³ *Ibid.*, **78**, 73, 1933.

⁴ *The Stars of High Luminosity*, especially chap. xv, 1930; *M.N.*, **92**, 368, 1932. See also *Harvard Circ.*, Nos. 252 and 256, 1924; *Nature*, **113**, 783, 1924; *Harvard Circ.*, No. 365, 1931.

⁵ *Ap. J.*, **71**, 191, 1930.

⁷ *Ibid.*, **78**, 219, 1933.

⁶ *Ibid.*, **70**, 141, 1929.

⁸ *Ibid.*, **71**, 221, 1930.

⁹ Taken from *Pub. Dom. Ap. Obs.*, **5**, No. 2, 1931, with the exception of 67 Oph, which is there given as B8s; in *ibid.*, No. 1, however, this star is called B3s. I have therefore regarded its Victoria type as B5.

TABLE I
OBSERVATIONAL DATA

BS No.	STAR	1900		MAG.	SPECTRUM		LUMINOSITY CLASS	LINE-WIDTH CLASS	NO. OF PLATES
		α	δ		Harv.	Vict.			
1228.....	ξ Per	3 ^h 52 ^m 5	+35° 30'	4.05	Oe5	O7nk	<i>d</i>	II	1
1879.....	λ Ori	5 29.6	+ 9 52	3.66	Oe5	O8sk	<i>g</i>	I	1
1895.....	θ^1 Ori	5 30.4	- 5 27	5.36	Oe5	O7k	<i>d</i>	I	1
1896.....	Bond 640	5 30.4	- 5 27	6.85	Oe5	Bo	<i>d</i>	II	1
1899.....	ι Ori	5 30.5	- 5 59	2.87	Oe5	O8sk	<i>d</i>	II	2
2456.....	S Mon	6 35.5	+ 9 59	4.68	Oe5	O7sk	<i>g</i>	I	2
2781.....	29 CMA	7 14.5	-24 23	4.90	Oe	O9sfk	<i>g</i>	I	2
2782.....	7 CMA	7 14.6	-24 46	4.40	Oe5	O9sk	<i>d</i>	II	1
8428.....	19 Cep	22 2.1	+61 48	5.17	Oe5	Ook	<i>g</i>	I	2
8622.....	10 Lac	22 34.8	+38 32	4.91	Oe5	O9sk	<i>d</i>	I	1
130.....	κ Cas	0 27.3	+62 23	4.24	Bo	Bok	<i>g</i>	I	1
1542.....	α Cam	4 44.1	+66 10	4.38	Bo	O9sek	<i>g</i>	II	1
1852.....	δ Ori	5 26.9	- 0 22	2.48	Bo	Bok	<i>d</i>	II	2
1876.....	ϕ^1 Ori	5 29.3	+ 9 25	4.53	Bo	Bossk	<i>d</i>	I	3
1903.....	ϵ Ori	5 31.1	- 1 16	1.75	Bo	Bok	<i>g</i>	I	1
1948.....	ζ Ori	5 35.7	- 2 0	2.05	Bo	Bonk	<i>d</i>	II	1
2004.....	κ Ori	5 43.0	- 9 42	2.20	Bo	Bok	<i>g</i>	I	1
4133.....	ρ Leo	10 27.5	+ 9 49	3.85	Bop	Bosk	<i>g</i>	II	1
6165.....	7 Sco	16 29.6	-28 1	2.91	Bo	Brs	<i>d</i>	I	1
1203.....	ζ Per	3 47.8	+31 35	2.91	B1	B1s	<i>g</i>	II	1
1220.....	ϵ Per	3 51.1	+39 43	2.96	B1	B2	<i>d</i>	II	1
2204.....	β CMA	6 18.3	-17 54	1.99	B1	B1ss	<i>g</i>	I	2
2618.....	ϵ CMA	6 54.7	-28 50	1.63	B1	B1s	<i>g</i>	II	1
5984.....	β Sco	15 59.6	-19 32	2.90	B1	B2k	<i>d</i>	II	1
39.....	γ Peg	0 8.1	+14 38	2.87	B2	B2ss	<i>d</i>	I	2
779.....	δ Cet	2 34.4	- 0 6	4.04	B2	B2s	<i>d</i>	I	3
1790.....	γ Ori	5 19.8	+ 6 16	1.70	B2	B2s	<i>d</i>	II	1
2135.....	χ^2 Ori	5 58.0	+20 8	4.71	B2p	B2ssk	<i>g</i>	I	1
8279.....	9 Cep	21 35.2	+61 38	4.87	B2p	B2sk	<i>g</i>	II	1
153.....	ζ Cas	0 31.4	+53 21	3.72	B3	B2sk	<i>d</i>	I	1
154.....	π And	0 31.5	+33 10	4.44	B3	B3	<i>d</i>	I	1
542.....	ϵ Cas	1 47.2	+63 11	3.44	B3	B3s	<i>d</i>	I	1
1239.....	λ Tau	3 55.1	+12 12	3.3-4.2	B3	B3	<i>d</i>	II	1
1641.....	η Aur	4 59.5	+41 6	3.28	B3	B3	<i>d</i>	II	1
4590.....	31 Crv	11 55.7	-19 6	5.28	B3	B4n	<i>d</i>	II	1
5191.....	η UMa	13 43.6	+49 49	1.91	B3	B3n	<i>d</i>	II	1
6431.....	u Her	17 13.6	+33 12	4.8-5.3	B3	B3	<i>d</i>	II	1
6453.....	θ Oph	17 15.9	-24 54	3.37	B3	B2	<i>d</i>	I	1
6588.....	ι Her	17 36.6	+46 4	3.79	B3	B3s	<i>d</i>	I	2
6787.....	102 Her	18 4.5	+20 48	4.32	B3	B2sk	<i>d</i>	II	1
7298.....	η Lyr	19 10.4	+38 58	4.46	B3	B3s	<i>d</i>	I	1
7474.....	σ Aql	19 34.3	+ 5 10	5.17	B3	B3	<i>d</i>	II	1
8926.....	1H. Cas	23 25.4	+58 0	4.89	B3	B3k	<i>d</i>	II	1

TABLE I—*Continued*

BS No.	STAR	1900		MAG.	SPECTRUM		LU- MINOS- ITY CLASS	LINE- WIDTH CLASS	NO. OF PLATES
		α	δ		Harv.	Vict.			
280.....	α Scl	0 ^h 53 ^m 8	-29° 54'	4.39	B5	B5	<i>d</i>	I	I
1149.....	20 Tau	3 39.9	+24 4	4.02	B5	B9s	<i>d</i>	I	I
2343.....	ν Gem	6 23.0	+20 17	4.06	B5	B5ne	<i>d</i>	I	I
2657.....	γ CMa	6 59.2	-15 29	4.07	B5	B8	<i>d</i>	I	I
2745.....	27 CMa	7 10.2	-26 11	4.66	B5p	B5	<i>d</i>	II	I
6092.....	τ Her	16 16.7	+46 33	3.91	B5	B7s	<i>d</i>	I	I
6396.....	ξ Dra	17 8.5	+65 50	3.22	B5	B8s	<i>d</i>	I	I
6714.....	67 Oph	17 55.6	+2 56	3.92	B5p	B5 ⁹	<i>g</i>	I	I
7852.....	ϵ Del	20 28.4	+10 58	3.98	B5	B7	<i>d</i>	I	I
7963.....	λ Cyg	20 43.5	+36 7	4.47	B5	B6e	<i>d</i>	II	I
8523.....	2 Lac	22 16.9	+46 2	4.66	B5	B5	<i>d</i>	I	I
936.....	β Per	3 1.6	+40 34	2.1-3.2	B8	.....	<i>d</i>	I	I
1713.....	β Ori	5 9.7	-8 19	0.34	B8p	.....	<i>g</i>	I	I
1791.....	β Tau	5 20.0	+28 31	1.78	B8	.....	<i>d</i>	I	I
3623.....	κ Cnc	9 2.3	+11 4	5.14	B8	.....	<i>d</i>	I	I
4662.....	γ Crv	12 10.7	-16 59	2.78	B8	.....	<i>d</i>	I	I
6812.....	μ Sgr	18 7.8	-21 5	4.01	B8p	.....	<i>g</i>	II	I
7906.....	α Del	20 35.0	+15 34	3.86	B8	.....	<i>d</i>	II	I
8541.....	4 Lac	22 20.5	+48 58	4.64	B8p	.....	<i>g</i>	I	I
8634.....	ξ Peg	22 36.5	+10 19	3.61	B8	.....	<i>d</i>	II	I
8965.....	17 And	23 33.2	+42 43	4.28	B8	.....	<i>d</i>	II	I
223.....	ν Cas	0 43.2	+50 25	5.03	B9	.....	<i>d</i>	I	I
1204.....	+62° 628	3 48.6	+62 47	4.87	B9	.....	<i>d</i>	I	I
4116.....	δ Sex	10 24.4	-2 14	5.24	B9	.....	<i>d</i>	II	I
5982.....	ν Her	15 59.7	+46 19	4.64	B9	.....	<i>d</i>	I	I
7236.....	λ Aql	19 0.9	-5 2	3.55	B9	.....	<i>d</i>	II	I
7750.....	κ Cep	20 12.3	+77 25	4.40	B9	.....	<i>d</i>	I	I

The number of spectra on each kind of emulsion, and a mean value for the weakest line measurable for each of the kinds principally used, are given in Table II.

Lines fainter than could be measured by the method about to be described could be seen on the Process plates of sharp-line stars. In the wide-line spectra, however, especially those on fast grainy plates, the situation was reversed; lines could be measured by the present method that could neither be found visually nor measured satisfactorily on tracings. This feature has made possible the study of many wide-line spectra in stars too faint to permit the securing of Process spectrograms.

The plates were chosen so that every star of type B9 or earlier for

which a well-guided, adequately exposed plate was available was represented by at least one spectrogram. The total absorptions were measured on a photoelectric microphotometer¹⁰ belonging to Dr. H. Rosenberg. In this photometer, a microscope objective projects a reduced image of a uniformly illuminated diaphragm (square, in this case) on the plate being measured. The diaphragm image must be large enough to include all of the line being measured. A second microscope objective produces an image of this region of the plate on the mirror of a Lummer-Brodhun cube, whence almost all the

TABLE II
PHOTOGRAPHIC EMULSIONS USED

Emulsion	No. of Spectra	Weakest Line Measurable
Eastman 40.....	34	0.08 A
Eastman Process.....	30	.04
Eastman Hyper-press.....	13	0.06
Imperial Eclipse Soft.....	3	.....
Eastman IV-O Spectrographic....	1	.....
Eastman Supersensitive Portrait Film.....	1	.....

light passes through a neutral wedge to the photocell. An electrometer is used to indicate balance between the output of this cell and that of another photocell, illuminated by the same lamp, which is used for compensation, the position of the neutral wedge being varied until this balance occurs. The setting of the wedge can easily be read to 0.1 mm, or about 0.001 mag. Repeated measures on one point of a plate are useless; the steadiness of the electrical circuits of this instrument is such that the readings would all be the same.

The procedure in measuring was as follows: the spectrum was first oriented parallel to one screw of the plate carriage, by inspection through the setting eyepiece. This eyepiece, focused on the mirror of the Lummer-Brodhun prism, gives the operator a view not only of the portion of the plate illuminated by the measuring beam but of the neighboring portion of the plate as well; this feature made

¹⁰ For a more complete description of the instrument than is given below, see *Zs. f. Instrumentenkunde*, 45, 313, 1925, or *Handb. der Astroph.*, 2, Part 1, p. 425, 1929.

easy such things as the orientation mentioned, the recognition of the spectral region, and the avoidance of bad flaws or scratches on the plate. When the plate had been oriented and the sensitivity of the electrometer adjusted to cover the range of densities needed, five (sometimes more) wedge readings were taken for each line, as follows: one with the line centered in the diaphragm; two on clear film opposite the line (one above and one below the comparison spectrum); and two on the continuous spectrum, at either side of the line. Where the density of the continuous spectrum was changing fast, two places on each side were measured. From this last group, a reading was deduced for the continuous spectrum at the position of the line. The mean of the clear film readings was used in the reductions as the zero point of that line. In addition to measures on the spectrum, three points near the center of each of the measurable spots imprinted by the tube sensitometer on each spectrogram were measured, and clear film readings were made on either side of each spot.

From the difference in wedge reading (clear film — spot) for each sensitometer spot, plotted against the known magnitude differences between spots, a characteristic curve was drawn for each plate. By means of this curve, the interval in wedge reading between line and continuous background at the position of the line was converted into a magnitude difference, and the total absorption for each line was deduced.

Table III gives the measured intensities, in angstroms of total absorption, for each line measured in more than one or two stars. As will be shown later, the values given for the hydrogen lines are not actual total absorptions, but they are consistent fractions of the total absorptions regardless of broadening due to rotation or to Stark effect. Included also in Table III, in italics, are eye estimates of the total absorptions of some lines which were not measurable, because of weakness, or plate flaws. These estimates were calibrated by means of the measured intensities of other lines in the same spectrum or in other spectra of similar type and line width. An entry in the table such as < 0.08 indicates that the line was absent (that is, it could neither be seen nor measured) and that the weakest line shown with any certainty on that plate had an intensity of approxi-

TABLE III
TOTAL ABSORPTIONS*

Wave-Length	ξ Per Oe5	λ Ori Oe5	θ^1 Ori Oe5	Bond 640 Oe5	ϵ Ori Oe5	S Mon Oe5	20 CMa Oe	τ CMa Oe5	19 Cep Oe5	10 Lac Oe5
<i>He I</i>										
4472....	0.59	0.61	0.52	0.91	0.87	0.51	0.70	0.96	0.97	0.81
4026....	0.58	0.59	0.48	1.05	0.60	0.49	0.55	0.65	0.53	0.64
4713....	0.31	0.13	0.28	0.13	0.22	0.16	0.34	0.23	0.33	0.23
4121....	0.09	0.16	0.12	0.34	0.15	0.08	0.05	0.18	0.14	0.13
4388....	0.20	0.21	0.27	0.65	0.34	0.21	0.16	0.59	0.20	0.32
4144....	0.12	0.11	0.13	0.57	0.22	0.14	0.08	0.41	0.16	0.19
4009....	0.06	0.06	0.05	0.46	0.15	0.04	0.02	0.18	0.02	0.12
3965....			0.19							
4438....										
4169....		0.03			0.04					0.03
<i>He II</i>										
4200....	0.33	0.28	0.48	0.10	0.26	0.33	0.24	0.25	0.15	0.18
4542....	0.55	0.53	0.28	<0.10	0.42	0.44	0.48	0.39	0.30	0.46
4686....	0.32	0.40	0.60	0.25	0.44	0.49	emis.	0.26	0.22	0.71
<i>H</i>										
4102....	1.22	1.37	1.31†	2.18†	1.42	1.16	1.09	1.68	1.32	1.09
4340....	1.51	1.38	1.51†	2.85†	1.81	1.39	1.11	1.79	1.36	1.57
4861....	1.78							1.52		
<i>Si IV</i>										
4089....	0.10	0.22	0.04	0.18	0.24	0.12	0.14	0.39	0.43	0.22
4116....	0.06	0.16	0.04	0.12	0.12	0.04	0.13	0.34	0.32	0.11
4212....		0.07			0.12					0.04
<i>Si III</i>										
4552....					0.19				0.20	0.08
4507....									0.16	0.04
4574....									0.16	0.03
<i>Si II</i>										
4128....										
4131....										
<i>N III</i>										
4097....	0.15	0.19	0.08	0.10	0.16	0.15	0.54	0.24	0.37	0.31
4379....		0.07			0.09	0.06		0.09		0.07
<i>N II</i>										
3995....										
4237....										
4242....										
<i>Mg II</i>										
4481....	0.12	0.06	0.05	<0.10	0.10	0.07	0.05	0.08	0.11	0.05
<i>C II</i>										
4267....										

* Intensities are in angstroms of total absorption. Italics indicate estimated values. Hydrogen intensities are not actual total absorptions; see text.

† These values were determined from tracings.

TABLE III—*Continued*

Wave-Length	κ Cas Bo	α Cam Bo	δ Ori Bo	ϕ^2 Ori Bo	ϵ Ori Bo	ζ Ori Bo	κ Ori Bo	ρ Leo Bop	τ Sco Bo	ξ Per B1
<i>He I</i>										
4472.....	0.66	1.19	0.75	1.29	0.84	1.20	1.04	0.91	1.07	0.95
4026.....	0.58	0.86	0.46	0.78	0.56	0.74	0.62	0.68	0.71	0.61
4713.....	0.19	0.34	0.25	0.53	0.19	0.25	0.35	0.34	0.17	0.39
4121.....	0.41	0.25	0.15	0.36	0.27	0.20	0.27	0.38	0.25	0.30
4388.....	0.45	0.30	0.25	0.72	0.38	0.36	0.44	0.41	0.60	0.47
4144.....	0.30	0.20	0.15	0.57	0.23	0.26	0.28	0.33	0.37	0.37
4009.....	0.29	0.13	0.11	0.29	0.15	0.12	0.17	0.31	0.23	0.30
3965.....				0.12		0.13				0.21
4438.....										
4169.....			0.01		0.03	0.04	0.06	0.08	0.02	
<i>He II</i>										
4200.....	<0.08	0.23	0.13	0.04	0.10	0.24	0.06	0.05	0.07	
4542.....	0.10	0.26	0.17	0.02	0.14	0.33	0.04	<0.10	0.15	
4686.....	0.10	0.05	0.23	0.52	0.08	0.18	0.20	<0.10	0.27	0.02
<i>H</i>										
4102.....	0.99	1.71	1.03	1.50	1.11	1.52	1.12	0.98	1.48	1.08
4340.....	1.10	1.36	1.25	2.05	1.21	1.82	1.54	1.53	2.09	1.55
4861.....										
<i>Si IV</i>										
4089.....	0.27	1.00	0.32	0.26	0.62	0.38	0.43	0.18	0.09	0.09
4116.....	0.19	0.57	0.21	0.20	0.50	0.35	0.28	0.08	0.06	0.03
4212.....					0.04				0.03	
<i>Si III</i>										
4552.....	0.64	0.15	0.10	0.54	0.32	0.22	0.36	0.55	0.20	0.45
4567.....	0.50	0.10	0.06	0.48	0.24	0.13	0.23	0.50	0.17	0.37
4574.....	0.29	<0.10	0.04	0.27	0.14	0.10	0.13	0.29	0.14	0.18
<i>Si II</i>										
4128.....										
4131.....										
<i>N III</i>										
4097.....	0.08	0.87	0.15	0.13	0.37	0.29	0.26	0.10	0.20	0.11
4379.....		0.25			0.06	0.03	0.04		0.07	
<i>N II</i>										
3995.....										0.22
4237.....										
4242.....										
<i>Mg II</i>										
4481.....	0.06	0.10	0.02	0.15	0.08	0.15	0.15	0.27	0.11	0.20
<i>C II</i>										
4267.....				0.18						0.19

TABLE III—*Continued*

Wave-Length	ϵ Per B1	β CMa B1	ϵ CMa B1	β Sco B1	γ Peg B2	δ Cet B2	γ Ori B2	χ^e Ori B2p	η Cep B2p	ξ Cas B3
<i>He I</i>										
4472....	1.41	0.90	0.78	0.91	1.42	1.36	1.39	0.90	1.00	1.42
4026....	1.07	0.98	0.75	0.49	0.98	1.13	1.19	0.66	0.57	1.00
4713....	0.32	0.32	0.29	0.15	0.31	0.43	0.51	0.25	0.42	0.31
4121....	0.42	0.38	0.12	0.23	0.34	0.46	0.39	0.30	0.34	0.34
4388....	0.80	0.62	0.53	0.42	0.92	0.91	0.83	0.73	0.48	0.97
4144....	0.53	0.46	0.30	0.31	0.69	0.76	0.72	0.40	0.33	0.78
4009....	0.40	0.44	0.30	0.21	0.45	0.62	0.56	0.40	0.26	0.52
3965....	0.49	0.28	.....	0.23	0.26	0.19	0.23	0.48	0.29	0.20
4438....	.....	0.09	0.12	.....	0.09	.....	.....	.....	0.01	0.08
4169....	.....	0.05	.....	0.05	0.07	.....	0.10	.....	0.04	0.12
<i>He II</i>										
4200....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
4542....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
4686....	.....	.....	.....	0.04	.....	.....	.....	.....	.....	.....
<i>H</i>										
4102....	1.79	1.56	.....	1.41	1.82	2.05	2.13	1.14	1.07	1.74
4340....	2.12	1.52	1.19	1.58	2.32	2.46	2.96	1.27	1.33	2.25
4861....	.....	1.82	.....	.....	.....	.....	2.71	.....	.....	.....
<i>Si IV</i>										
4089....	0.20	0.11	0.06	0.08	0.02	.....	.....	.....	.....	.....
4116....	0.07	0.01	0.03	0.02	.....	.....	.....	.....	0.01	.....
4212....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
<i>Si III</i>										
4552....	0.25	0.36	0.45	0.18	0.20	0.13	0.21	0.58	0.45	0.18
4567....	0.15	0.30	0.34	0.13	0.15	0.06	0.21	0.44	0.32	0.14
4574....	0.10	0.14	0.21	0.10	0.10	0.06	0.16	0.42	0.19	0.09
<i>Si II</i>										
4128....	.....	.....	.....	.....	.....	.....	.....	.....	0.09	0.01
4131....	.....	.....	.....	.....	.....	.....	.....	.....	0.15	0.03
<i>N III</i>										
4097....	0.10	0.02	0.02	0.03	.....	.....	.....	.....	.....	.....
4379....	.....	.....	.....	0.01	.....	.....	.....	.....	.....	.....
<i>N II</i>										
3995....	0.30	0.18	0.20	0.08	0.06	0.08	0.11	0.54	0.16	0.06
4237....	.....	0.03	.....	.....	0.01	.....	.....	.....	0.03	.....
4242....	.....	0.07	.....	.....	0.04	.....	.....	.....	0.04	.....
<i>Mg II</i>										
4481....	0.31	0.18	0.20	0.14	0.24	0.28	0.21	0.28	0.34	0.32
<i>C II</i>										
4267....	<0.15	0.17	0.26	0.08	0.17	0.24	0.25	0.16	0.22	0.20

TABLE III—*Continued*

Wave-Length	π And B ₃	ϵ Cas B ₃	λ Tau B ₃	η Aur B ₃	ζ Crv B ₃	η UMa B ₃	α Her B ₃	θ Oph B ₃	ι Her B ₃	$\iota\sigma$ Her B ₃
<i>He I</i>										
4472....	0.84	0.81	0.93	1.06	0.85	1.08	1.80	1.13	1.18	1.14
4926....	0.72	0.64	0.85	0.83	0.80	0.78	0.99	1.13	1.00	0.84
4713....	0.13	0.17	0.15	0.27	0.35	0.08:	0.52	0.31	0.38	0.24
4121....	0.04:	0.11	0.14	0.17	0.23	0.11	0.36	0.41	0.20	0.25
4388....	0.54	0.47	0.45	0.59	0.42	0.64	1.11	0.71	0.82	0.81
4144....	0.45	0.42	0.46	0.55	0.54	0.47	1.17	0.59	0.66	0.58
4009....	0.31	0.25	0.36	0.33	0.37	0.31	0.45	0.54	0.36	0.47
3965....	.....	.....	0.45:	0.24	.....	.....	.....	.....	0.36	0.33
4438....	0.04	0.03	0.12	0.12	.....	0.09	.....	0.03	0.14	0.08
4169....	.....	0.03	0.19	0.03	0.09	0.06	0.25	0.12	0.09	0.08
<i>He II</i>										
4200....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
4542....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
4686....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
<i>H</i>										
4102....	2.60	1.88	2.14	2.27	2.17	2.00	2.84	1.87	2.22	1.51
4340....	3.28	2.46	2.51	2.93	2.17	2.58	3.39	2.38	2.96	2.00
4861....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
<i>Si IV</i>										
4089....	.....	.....	.....	.....	.....	.....	.....	0.05	.....	.....
4116....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
4212....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
<i>Si III</i>										
4552....	0.05	0.04:	0.20:	<0.06	0.37	0.07:	0.46	0.21	0.16	0.15
4567....	0.04:	0.02	0.10:	<0.06	0.29	0.04:	0.29	0.13	0.12	0.11
4574....	0.03:	0.02	0.04:	<0.06	0.17	0.02:	0.14	0.13	0.10	0.07
<i>Si II</i>										
4128....	0.04	0.06	0.08	0.02	0.05:	0.04	0.06	<0.08	0.07	0.01:
4131....	0.04	0.08	0.06	0.05	0.05:	0.06	0.12	<0.08	0.09	0.02:
<i>N III</i>										
4097....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
4379....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
<i>N II</i>										
3995....	0.06	0.02:	0.15	0.05	0.10	0.01:	0.10:	0.05	0.02	0.08
4237....	.....	.....	.....	.....	.....	.....	.....	.....	.....	0.04:
4242....	.....	.....	.....	.....	.....	.....	.....	.....	.....	0.06:
<i>Mg II</i>										
4481....	0.31	0.24	0.44	0.27	0.21	0.35	0.67	0.20	0.26	0.20
<i>C II</i>										
4267....	0.14	0.15	0.17	0.14	0.11	0.15	0.34	0.09	0.20	0.20

TABLE III—*Continued*

Wave-Length	η Lyr B ₃	σ Aql B ₃	π H. Cas B ₃	α Scl B ₅	20 Tau B ₅	ν Gem B ₅	γ CMa B ₅	27 CMa B _{5p}	τ Her B ₅	ξ Dra B ₅
<i>He I</i>										
4472....	0.88	1.28	1.32	0.37	0.55	0.77	0.27	1.69	0.88	0.47
4026....	0.76	0.70	1.01	0.38	0.37	0.51	0.27	1.35	0.82	0.41
4713....	0.23	0.29	0.51	0.21	0.13	0.27	0.15	0.48	0.21	0.18
4121....	0.19	0.12	0.14	0.04	0.06	0.15	0.06	0.33	0.08	0.03
4388....	0.52	0.81	0.71	0.21	0.35	0.54	0.29	0.77	0.66	0.28
4144....	0.46	0.65	0.55	0.28	0.21	0.39	0.14	0.83	0.35	0.22
4009....	0.42	0.30	0.39	0.07	0.08	0.18	0.10	0.57	0.24	0.06
3965....	0.17									
4438....	0.09	0.10								
4169....	0.07	0.04								
<i>He II</i>										
4200....										
4542....										
4686....										
<i>H</i>										
4102....	1.89	1.78	2.44	2.64	2.43	2.13	2.80	2.49	2.75	2.45
4340....	2.31	2.56	2.81	3.24	3.28	2.70	3.18	3.12	3.36	3.22
4861....				4.02			4.19			
<i>Si IV</i>										
4089....										
4116....										
4212....										
<i>Si III</i>										
4552....	0.08	0.38	0.13					0.24		0.07
4567....	0.04	<0.25	0.13							
4574....	0.01	<0.25	0.09							
<i>Si II</i>										
4128....	0.07	0.05	0.04	0.09	0.06	0.18	0.08	<0.20	0.08	0.11
4131....	0.09	0.05	0.04	0.14	0.10	0.15	0.08	<0.20	0.08	0.12
<i>N III</i>										
4097....										
4379....										
<i>N II</i>										
3995....	0.04	0.07	0.06							
4237....										
4242....										
<i>Mg II</i>										
4481....	0.26	0.27	0.39	0.25	0.31	0.43	0.32	0.16	0.33	0.31
<i>C II</i>										
4267....	0.16	0.21	0.10	0.17	0.12	0.10	0.08	0.10	0.12	0.05

TABLE III—*Continued*

Wave-Length	67 Oph B5p	ε Del B5	λ Cyg B5	2 Lac B5	β Per B8	β Ori B8p	β Tau B8	κ Cnc B8	γ Crv B8	μ Sgr B8p
<i>He I</i>										
4472.....	0.62	0.44	0.74	0.69	0.78	0.38	0.48	0.30	0.19	0.33
4026.....	0.62	0.43	0.70	0.51	0.61	0.29	0.40	0.25	0.25	0.30
4713.....	0.32	0.22	0.44	0.08	0.54	0.21	0.07	<0.05	0.07	<0.05
4121.....	0.16	0.05	0.12	0.09	0.10	0.08	0.05	0.03	0.03	0.06
4388.....	0.47	0.34	0.50	0.27	0.20	0.36	0.26	0.14	0.15	0.33
4144.....	0.34	0.21	0.35	0.26	0.15	0.14	0.19	0.08	0.07	0.25
4009.....	0.26	0.08	0.28	0.16	0.18	0.15	0.10	0.03	0.05	0.20
3905.....	0.14	.....	0.43	.....	.....	0.18	.....	.....	.....	.....
4438.....	0.06	.....	.....	.....	.....	.....	.....	.....	.....	.....
4169.....	0.02	0.02	0.06	.....	.....	0.04	.....	.....	.....	.....
<i>He II</i>										
4200.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
4542.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
4686.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
<i>H</i>										
4102.....	1.72	2.55	2.85	2.46	3.68	1.09	2.48	3.04	2.60	1.36
4340.....	2.22	2.76	3.32	3.05	4.31	1.15	3.22	3.67	3.23	1.38
4861.....	.....	.....	.....	.....	5.95	1.47	.....	5.14	.....	.....
<i>Si IV</i>										
4089.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
4116.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
4212.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
<i>Si III</i>										
4552.....	0.12	0.04	0.07	.....	.....	.....	.....	.....	.....	.....
4567.....	0.10	.....	0.04	.....	.....	.....	.....	.....	.....	.....
4574.....	0.07	.....	.....	.....	.....	.....	.....	.....	.....	.....
<i>Si II</i>										
4128.....	0.13	0.08	0.15	0.07	0.15	0.15	0.15	0.14	0.11	0.28
4131.....	0.15	0.06	0.12	0.07	0.10	0.15	0.12	0.14	0.10	0.33
<i>N III</i>										
4097.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
4379.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
<i>N II</i>										
3995.....	0.05	.....	0.14	.....	.....	0.07	.....	.....	.....	.....
4237.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
4242.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
<i>Mg II</i>										
4481.....	0.42	0.24	0.34	0.42	0.64	0.44	0.30	0.31	0.22	0.48
<i>C II</i>										
4267.....	0.26	0.08	0.18	0.16	<0.08	0.13	0.04	0.08	0.03	0.10

TABLE III—Continued

Wave-Length	α Del B8	γ Lac B8p	ξ Peg B8	ι And B8	ν Cas B9	+62° 628 B9	δ Sex B9	υ Her B9	λ Aql B9	κ Cep B9
<i>He I</i>										
4472.....	0.34	0.26	0.29	0.26	0.40	0.15	0.27	0.18	0.27	0.22
4026.....	0.31	0.34	0.18	0.30	0.32	0.20	0.24	0.31	0.20	0.15
4713.....	0.26	0.05	0.04	0.17	0.05	0.10	<0.10	0.06	0.15	0.08
4121.....	0.09	0.03	0.03	0.06	0.05	<0.07	0.10	0.05	<0.10	0.10
4388.....	0.30	0.24	0.18	0.25	0.09	0.14	0.26	0.14	0.25	0.29
4144.....	0.14	0.23	0.05	0.13	0.21	0.02	0.14	0.06	0.07	0.08
4009.....	0.06	0.05	0.02	0.08	0.03	0.07	<0.10	0.04	<0.10	0.08
3905.....										
4438.....										
4169.....										
<i>He II</i>										
4200.....										
4542.....										
4686.....										
<i>H</i>										
4102.....	3.34	2.41	2.72	3.02	3.27	3.16	3.15	flaw	3.53	3.67
4340.....	4.32	2.73	3.20	3.79	4.00	4.10	4.05	3.88	4.53	4.55
4861.....	5.56			5.16	8.83	5.48		4.84	5.74	5.66
<i>Si IV</i>										
4089.....										
4116.....										
4212.....										
<i>Si III</i>										
4552.....										
4567.....										
4574.....										
<i>Si II</i>										
4128.....	0.07	0.18	0.06	0.20	0.04	0.07	0.09	0.08	<0.10	0.18
4131.....	0.10	0.23	0.06	0.19	0.04	0.14	0.09	0.08	<0.10	0.13
<i>N III</i>										
4097.....										
4379.....										
<i>N II</i>										
3995.....										
4237.....										
4242.....										
<i>Mg II</i>										
4481.....	0.64	0.68	0.37	0.31	0.29	0.38	0.55	0.34	0.54	0.56
<i>C II</i>										
4267.....	0.08	0.08	0.01	0.10						

mately $0.08 \text{ \AA}$. The colon (:) is used to indicate an uncertain measure or estimate.

II. INVESTIGATION OF ERRORS

The theoretical difference between line intensities measured in the manner described and those determined by integration of profiles has been investigated by Öhman.¹¹ He found that where one is working on or near the straight-line portion of a characteristic curve whose slope is 1, and where the average density of continuous spectrum and

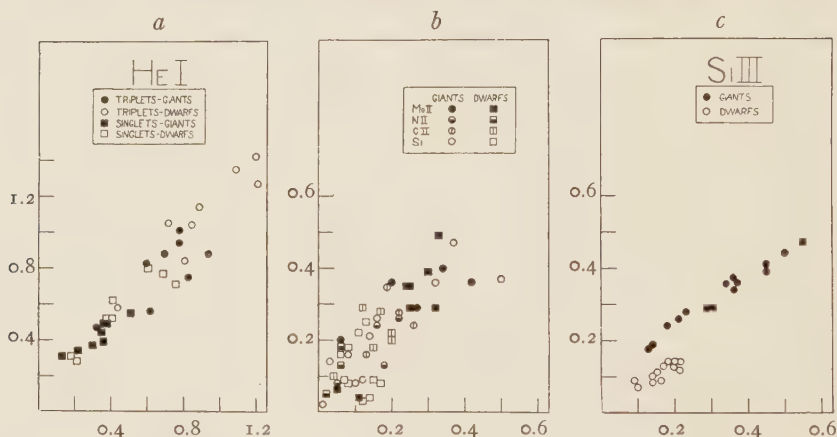


FIG. 1.—A comparison of the measured line intensities (abscissae) with (a) helium intensities given by Williams, (b) intensities of various other elements given by Williams, and (c) $Si \text{ III}$ intensities measured by Elvey. Units in both co-ordinates are angstroms total absorption.

line is 0.25 or more, the measured total absorptions should be greater than those determined from tracings by about 6 per cent. I did not reduce my intensities by this amount, however, since comparison of my results with those of Williams¹ showed a slight linear systematic difference, my values being smaller than his. These comparisons are shown in Figure 1, (a) and (b). Figure 1 (c), comparing my measures of lines of $Si \text{ III}$ with Elvey's,⁷ shows no such systematic difference.

Two sets of microscope objectives were used in the photometer during this investigation. The first, used for about three-fourths of

¹¹ *Arkiv f. Mat. Astron. och Fysik*, **20A**, No. 23, p. 24, 1927.

the measures, gave a diaphragm image on the plate of 0.27 mm, covering 5.5 Å at $H\delta$ and 7.0 Å at $H\gamma$. The other set of objectives illuminated a 0.22-mm square on the plate, equivalent to 4.4 Å at $H\delta$ or 5.7 Å at $H\gamma$. The latter was used only on spectra having fairly sharp lines, where poor guiding or narrowness of spectrum required it. Comparison of results obtained with the two magnifications was made by measuring three plates both ways. Systematic differences were found to be small—less than 0.01 Å for a line in two cases, and 0.05 Å in the third. Remeasurement and reduction independent of the first set of measures, on two plates, gave for the mean accidental error a value of 0.015 Å.

Systematic differences between measures on two spectrograms of the same star appear to be of a larger order, amounting to 0.10 Å for the mean of ten such cases. These differences are, of course, smaller for weak lines and larger for strong ones, in absolute value; but they very seldom exceed 20 per cent of the intensity of a strong line, while for the weakest lines they may be 75 per cent. A study of these differences convinced me that measures from one excellent plate were more trustworthy than means from two or three mediocre plates; hence, only the best plate available was measured for most of the stars studied.

Another possible source of error, in the case of binaries showing two spectra, lies in the apparent shallowing of each line by the continuous spectrum from the other component. This should be serious, however, only at phases when the lines are well separated. Examination of the plates which I had measured for the four stars on my list which were known to have two spectra¹² (β Sco, σ Aql, u Her, and 2 Lac) convinced me that the lines were not visibly double for any but that of u Herculis; the microphotometer tracing of this spectrum showed that any such correction would be inappreciable. Therefore, none was made.

For the hydrogen lines, the values given in Table III for all stars are systematically too small, as the square diaphragm did not include all of the wings of these lines, even in the O-type stars. This error was investigated by means of a tracing made with the recording microphotometer on a spectrum of ι Orionis; the total absorption

¹² J. H. Moore, *Lick Obs. Bull.*, No. 355, 1924.

measured on a profile of $H\delta$ obtained from this tracing was 1.57 Å; the value which I had measured with the Rosenberg photometer was 1.18 Å. When the wings of the profile were cut off as the square diaphragm had cut them off, the value measured on the tracing was reduced to 1.11 Å, agreeing, within 6 per cent, with the other value. The corresponding difference for $H\gamma$ was 8 per cent. The intensities given in Table III for the hydrogen lines in the two stars of the Trapezium in Orion, Bond 640 and θ^1 Orionis (Bond 628), were measured in this way also, that is, by making profiles from tracings, disregarding in these cases the sharp emission lines in the centers of the broad absorption lines, and cutting off the wings where the diaphragm would, had they been measured in the Rosenberg photometer. Judging from the case just mentioned, ι Orionis, the values so obtained should not differ appreciably from those which I would have obtained by measuring in my regular manner, if the emission had not been present.

Further comparison of results obtained by the present method with those from tracings was available from the helium and silicon intensities in three stars. For ι Orionis, seven lines were, on the average, 0.02 Å weaker on the tracing than in my regular measures. For Bond 640, three lines appeared 0.08 Å stronger on the tracing, in the mean. For θ^1 Orionis, λ 4472 was 0.14 Å weaker on the tracing; this was a rather dense and grainy plate. Thus, there seemed to be no appreciable systematic difference between the two methods of measuring total absorptions. A tracing was also made for η Herculis, the star having the widest strong helium lines of any measured, as determined by visual inspection. From this tracing it was evident that no corrections to the total absorptions for helium were necessary, as even in this spectrum λ 4472 was not as wide as the square illuminated in the Rosenberg instrument. Therefore, all values given in Table III are to be regarded as measured total absorptions, except those given for the Balmer lines. The latter, judging from the tracings mentioned above and from Figure 2, are about two-thirds of the total absorption when the latter is 2 Å, decreasing to one-third at a true value of 9 Å. This figure shows a comparison of my measures of hydrogen with those by Williams⁴ and by Elvey.⁵ Parts (a) and (b) of this figure show, also, that there is no appreciable

systematic difference between my measures on the giant and dwarf groups of stars (see sec. III, below), as points for giants and dwarfs tend to lie along the same line, in each case. Such a difference might be expected from the relatively stronger wings of the dwarf stars, which would cause the measured intensity of a hydrogen line in a dwarf to be smaller than that in a giant, while the true total absorptions in the two are the same.

A similar systematic difference in the ratio of measured to true total absorption would be anticipated between rotating and non-

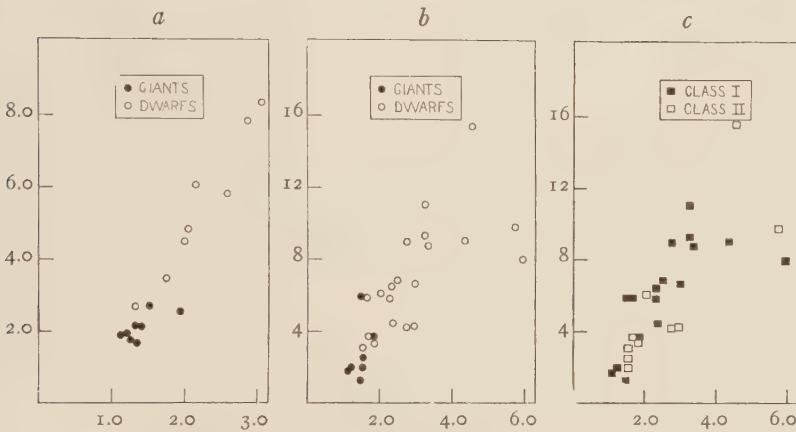


FIG. 2.—A comparison of the measured hydrogen intensities (abscissae) with (*a*) intensities measured by Williams, (*b*) intensities given by Elvey, divided according to luminosity, and (*c*) Elvey's values, divided according to line-width class. Units in both co-ordinates are angstroms total absorption.

rotating stars; the evidence of Figure 2 (*c*) would tend to show that this effect was inappreciable, since the points for rotating and non-rotating stars tend to lie along the same line. To test the matter further, the profiles given by Elvey⁵ for $H\gamma$ in β Canis Majoris and in β Orionis were arbitrarily broadened by an amount corresponding to an equatorial radial velocity of 120 km/sec at the limb, keeping the total absorption constant. The intensity that would be measured by my method, which takes into account only the central 7 Å of this line, was lowered by less than 3 per cent in either case, an amount well within the random errors of measurement. These profiles should

furnish a rigorous test, for the cores of these lines are almost of the same width as the image of the diaphragm used in measuring.

III. BEHAVIOR OF HYDROGEN LINES

The mean values measured for the hydrogen intensities for each Harvard spectral type are shown in Figure 3 (*a*). The slight dip from O to Bo is doubtless due to the larger proportion of dwarf stars (see below; also Table I) among the O's than among the Bo's. The ratio $H\delta:H\gamma$ averages 0.83, varying between 0.8 and 0.9 for the different subtypes. Williams¹ found that the hydrogen lines he measured, from $H\gamma$ to $H\zeta$, "have nearly equal intensities."

The stars measured in each subtype were divided into giants and dwarfs, following Struve's lists^{2,3} for all stars given there, and following his criteria as closely as possible for the remaining stars (italicized in Table I, third column from the right), especially as to the appearance of the hydrogen and helium lines, showing presence or absence of wings due to Stark effect. The striking difference between giants and dwarfs in the behavior of the mean of the two Balmer lines measured is shown in Figure 3 (*b*). The curves for the giants show a rise of only about 50 per cent for the stars later than B₃ as compared with the earlier ones. Among the dwarfs, the rise starts earlier and is very much steeper, increasing to almost double in the interval B₁–B₅.

It was deemed important to search for possible systematic differences between stars such as those used by Struve in his studies, which have for the most part sharp lines, and stars whose lines are broadened appreciably by axial rotation. For this purpose the measures of rotational broadening of λ 4481 of *Mg* II and λ 4472 of *He* I made by Miss Westgate¹³ were selected as an appropriate criterion, especially since her list covers all but four of the stars I measured. The other sixty-six stars I divided into two approximately equal groups: class I, including stars for which her adopted equatorial velocity of rotation is less than 65 km/sec; and class II, the stars with higher rotational velocities. The four stars not measured by her I classified by visual comparison with other stars of the same spectral

¹³ *A. J.*, 77, 141, 1933.

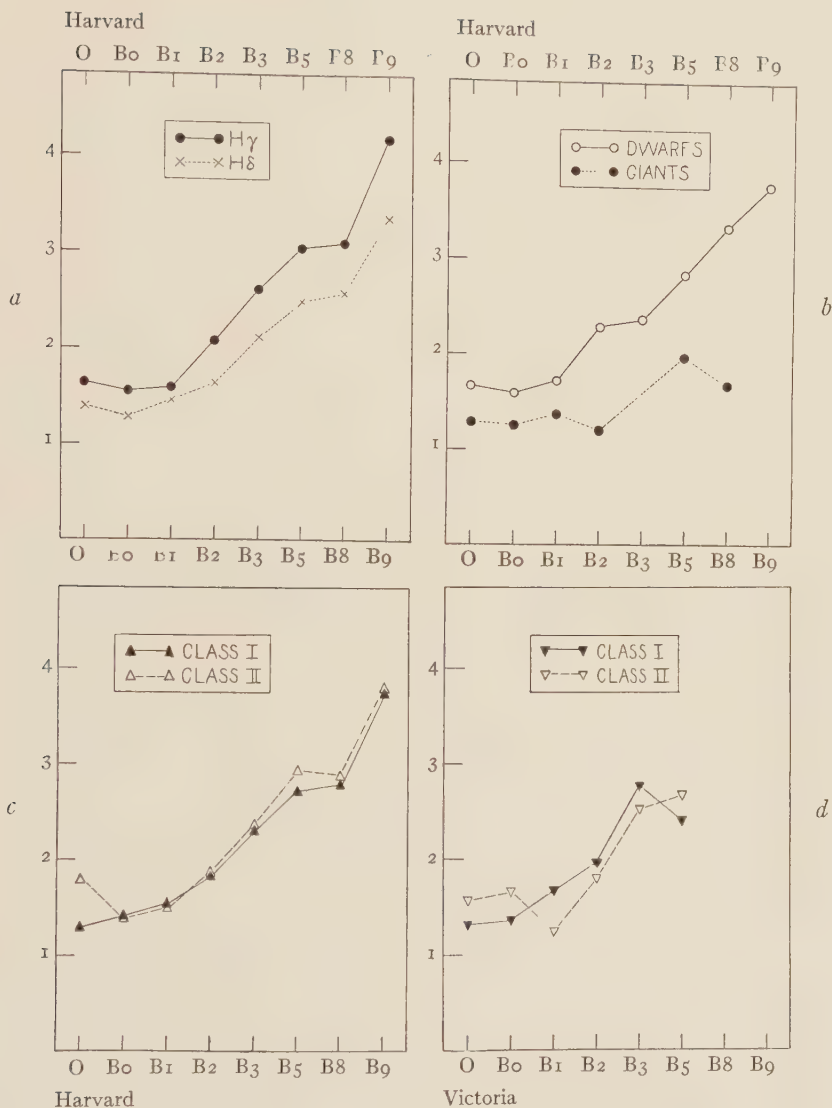


FIG. 3.—Behavior of measured hydrogen intensities with spectral type: (a) in all stars measured; (b) in giants and dwarfs, showing the mean of $H\gamma$ and $H\delta$; (c) in sharp-line (class I) and wide-line (class II) stars, also plotting the mean of $H\gamma$ and $H\delta$; and (d) similar to (c), except that Victoria types are substituted for Harvard. Ordinates are angstroms total absorption.

type and luminosity group. The line classes of these four are italicized in Table I.

The behavior with changing spectral type of the measured mean hydrogen intensity for the two classes of line widths is shown in Figure 3 (*c*). In type O, the apparent strengthening in the wide-line stars is partly an effect of absolute magnitude, since all four class II stars are dwarfs, while four of the six class I stars are giants. At B₅, absolute magnitude again accounts for part of the difference between the two groups; the remainder may easily be due to accidental errors. It appears, then, that rotational broadening has caused no systematic difference in classification of the stars of types O and B under the Harvard system, if we take hydrogen intensities as the indicator.

As this question was found to be especially significant in connection with the behavior of neutral helium (see sec. IV, below), a further study was made, retaining the line-width class of each star but using the spectral types assigned at Victoria,⁹ where this was B₆ or earlier. This included forty-nine of my seventy stars; the few stars on my list classified at Victoria as B₇ or later are all in class I; hence they are omitted in Figure 3 (*d*), which shows the results of this study. It might seem at first sight that the stars of class II in the types later than B₀ are classified too late with respect to the sharp-line group; but upon observing the reverse effect at B₄, 5, 6, and in general the large departures of both curves from smoothness, it seems to me that there is no definite systematic difference in intensity of hydrogen lines between rotating and non-rotating stars of the same Victoria spectral class.

IV. BEHAVIOR OF THE LINES OF NEUTRAL HELIUM

Figure 4 shows the behavior, with Harvard spectral type, of all the lines of neutral helium which were strong enough to be studied over the whole of the range of spectral types covered. For the sake of completeness the intensities of these seven lines were estimated in every star where they could not be measured. Where the line could not be found, its intensity was counted as zero in taking the mean for the spectral type. The dotted portion of the curve for λ 4026 indicates an allowance for blending with the *He* II line at λ 4024 in the O stars.

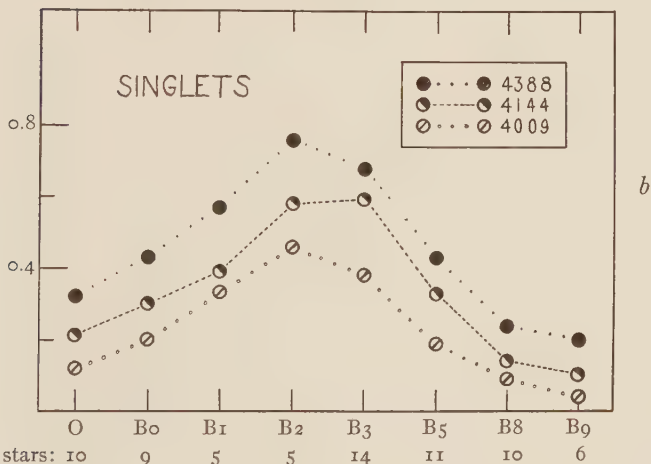
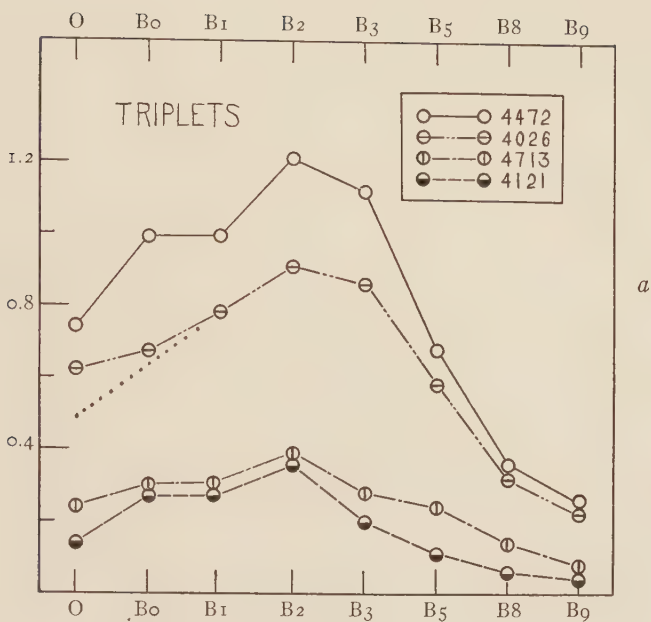


FIG. 4.—Behavior of helium intensities with spectral type, in all stars measured. Ordinates are angstroms total absorption.

The maximum at type B2 for all lines but one agrees with the results of other investigators.¹⁴ The one exception, the singlet λ 4144, is doubtless due to accidental errors, as may be seen from the close similarity to each other, in every respect but this, of the three singlet curves. From these curves, it is obvious that there is a definite difference in behavior between the lines of the singlet and triplet systems of this element. There is evidently no displacement of maximum intensity, from one system to the other; and the behavior of the two sets of curves on the low-temperature side of the maximum is similar in many respects, but on the hot side of the maximum, in the interval from O to B2, the slopes of the curves for triplets are definitely smaller than those for the singlets. Plotted as they are, with equal intervals between Harvard subtypes, the curves for the singlets are almost symmetrical about B2.3 or thereabouts, whereas there is a definite asymmetry in every one of the triplet curves, the left portion being flatter and higher. The effect, of course, is to give a sharper, better-defined maximum for the singlets. It may be seen, also, that the triplet-to-singlet ratio (λ 4472: λ 4388 is the best example) decreases definitely from type O to type B2, and then remains sensibly constant through type B8. The results by Struve¹⁵ and by Elvey¹⁶ are thus confirmed on the high-temperature side of maximum.

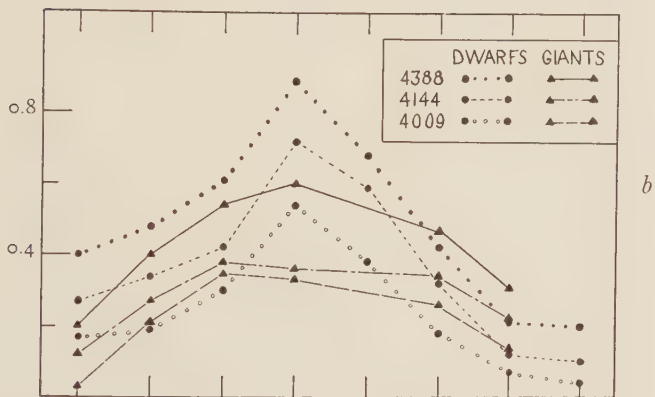
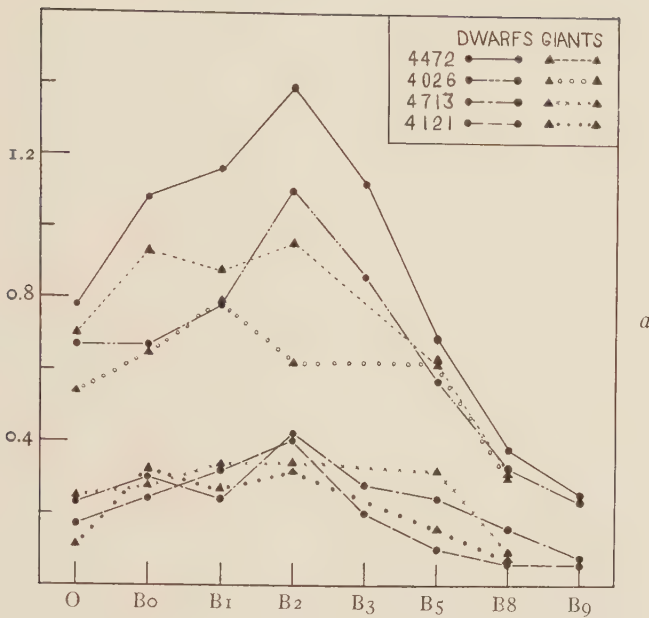
Another feature to be noted is that, as in the Balmer lines, there is a fading along each series, quite definite for the diffuse triplets in the hotter stars and for the singlets all through the interval studied.

Figure 5 shows the differences in the behavior of the helium lines between the giant and dwarf groups. In the latter, all of the lines have a well-defined sharp maximum at type B2, as has been observed by Struve, Williams, and others. The giants, on the other hand, show a flat maximum at B1, in all cases but one. It is suggested that the sharpness of the maximum in the dwarfs may be due to a tendency, in classifying, to bunch all of the stars having the strongest helium lines in one subdivision. The weakness of the hy-

¹⁴ Cf. Miss Payne, *The Stars of High Luminosity*, p. 90, 1930; Struve, *Ap. J.*, **78**, 82, 1933; Williams, *op. cit.*

¹⁵ *Ap. J.*, **78**, 82, 1933; also *ibid.*, **74**, 249, 1931.

¹⁶ *Ibid.*, **70**, 150, 1929.



No. of stars:	O	B ₀	B ₁	B ₂	B ₃	B ₅	B ₈	B ₉
Dwarfs:	6	4	2	3	14	10	7	6
Giants:	4	5	3	2	0	1	3	0

FIG. 5.—Behavior of helium intensities in dwarf and giant groups. (a) shows the triplets and (b) the singlet lines. Intensities are angstroms total absorption.

drogen lines in giants, allowing them to be classified earlier than dwarfs having helium lines of the same strength, may account for the difference in position of the maximum intensity between the two groups. The singlet and triplet groups of curves, for both giant and dwarf stars, retain in general the difference mentioned above, namely, that the triplets fade out more slowly on the hot side of maximum than do the singlets.

Considering the strongest and most accurately measured line in each system (again $\lambda 4388$ and $\lambda 4472$), it may be noted that the triplet line $\lambda 4472$ fades out more slowly, on either side of maximum, in giants than in dwarfs. For the singlet, $\lambda 4388$, the same is true in the later types; but in the interval B2 to O, the situation is reversed; the intensities in giants drop faster than those for dwarfs, if anything.

If these differences between singlets and triplets, depending upon luminosity, were due solely to the steeper gradient of line intensity in giants, we would expect to find the singlets intermediate in behavior, as they are in strength, between the diffuse and the sharp triplet lines. That this is not the case is best shown, perhaps, by using the stars of type O as an example. The triplets, in either series, are, on the average, about 25 per cent stronger in the dwarfs than in the giants; yet every one of the singlets is at least twice as strong in the dwarfs as in the giants. Thus, the triplet-singlet differences cannot be due entirely to the gradient effect.¹⁷

The differences I have found between singlets and triplets in giants and dwarfs are in essential agreement with those of Struve,¹⁸ on which he bases his suggestion that the *He I* anomaly may be explained by large departures from thermodynamic equilibrium, the departure being greater for a giant than for a dwarf.

At type B2, both $\lambda 4472$ and $\lambda 4388$ are about 50 per cent stronger in dwarfs than in giants, and the triplet $\lambda 4472$ is 50 per cent stronger in either class than its neighboring singlet $\lambda 4388$. At type B8, $\lambda 4472$ is still a little stronger in dwarfs than in giants; the singlet, however, is actually materially stronger in the giant stars. The other two members measured in the same singlet series confirm this

¹⁷ See Struve and Elvey, *ibid.*, **79**, 409, 1934.

¹⁸ *Ibid.*, **82**, 257, 1935, gives a summary of Struve's results on the *He I* intensities.

fact. It may be mentioned that only in the giants of type B8, as a group, does λ 4388 become as strong as λ 4472. This is contradictory to Struve's estimated data.¹⁹

It is interesting at this point to interject a study of a pair of stars of the same spectral type, B8, whose luminosities are known from non-spectroscopic criteria to be markedly different from each other.

TABLE IV
TOTAL ABSORPTIONS IN β ORIONIS AND β PERSEI

Element	λ	β Ori B8 Giant	β Per B8 Dwarf
<i>He</i> I triplets.....	4472	0.38	0.78
	4026	0.29	0.61:
	4713	0.21	0.54:
	4121	0.08	0.10
<i>He</i> I singlets.....	4388	0.36	0.20
	4144	0.14	0.15
	4009	0.15	0.18
<i>H</i>	4102	1.09	3.68
	4340	1.15	4.31
<i>Si</i> II.....	4128	0.15	0.15
	4131	0.15	0.10
<i>Mg</i> II.....	4481	0.44	0.64
<i>C</i> II.....	4267	0.13	<0.08

The rotational broadening in the two stars chosen is almost identical.¹³ The giant, β Orionis, is the brightest member of the Orion cluster, whose parallax has been reasonably well determined,²⁰ giving an absolute magnitude of -6.0 for this star. The dwarf, β Persei, has a good trigonometric parallax²¹ which agrees well with the parallax computed from the eclipsing binary system.²² The line intensities for the two stars are shown in Table IV.

Among the *He* I lines, it will be noted that the stronger "diffuse" triplets are enhanced in the dwarf (cf. Fig. 5), the weaker triplets are

¹⁹ *Ibid.*, 74, 249, 1931.

²⁰ Rasmuson, *Lund Medd.*, Ser. II, No. 26, p. 48, 1921.

²¹ Schlesinger, *General Catalogue of Stellar Parallaxes*, 2d ed., 1935.

²² Shapley, *Princeton Contr.*, No. 3, p. 83, 1915.

doubtful, and the singlets may be slightly stronger in the giant. Hydrogen is very much stronger in the dwarf (cf. Fig. 3 [b]), as is $Mg\ II$ (contrary to its usual behavior at B8; see Fig. 13, below). $Si\ II$ and $C\ II$ are both enhanced in the giant, as will be shown to be the general case. Thus in all but one of the features enumerated, this well-established giant and dwarf differ in the same manner as do the means for the giant and dwarf groups divided according to spectroscopic criteria.²³

It is also of interest to study the changes of line intensity with changing apparent magnitude in the brighter Bo stars of the Orion group. Rasmuson²⁰ lists the four stars ϵ , ζ , κ , and δ Orionis as members of the Orion cluster, for which he derives a parallax of $0''.0055$. These stars lie within an area in the sky about 5° by 10° . Assuming that these four stars are all at the same distance, the differences between their apparent magnitudes will of course be equal to the differences between their absolute magnitudes. Therefore, such a study might be expected to show, at least to some extent, the effects of changing luminosity on line intensity. The range in apparent magnitude, however, is only about three-fourths of a magnitude, which is rather a small fraction of the total dispersion in absolute magnitude at type Bo.

Figure 6 shows the intensities of lines of various elements in these four stars, plotted against their apparent magnitudes. The lines of neutral helium and of hydrogen, shown in part (a) of the diagram, do not display any enhancement in the less luminous stars, although that is their general tendency at Bo (see Figs. 3[b] and 5). There is, however, a similarity in behavior between $H\gamma$ and $\lambda\ 4472$, like that shown in Figure 7 (b), below. On the other hand, both $\lambda\ 4089$ of $Si\ IV$ and $\lambda\ 4097$ of $N\ III$, shown in part (b) of the figure, do show quite definitely the enhancement in the more luminous stars that is characteristic of their general behavior (see sec. V, below). The two lines of $He\ II$ plotted in part (c) also show fairly typical behavior; $\lambda\ 4542$ shows no definite trend; it will be shown to be only slightly strength-

²³ For further evidence on the luminosities of Struve's giants and dwarfs, see Miss E. T. R. Williams (*Ap. J.*, **75**, 386, 1932), and E. G. Williams (*op. cit.*).

ened in the dwarf group, in general, at B0. $\lambda 4686$, which will be demonstrated to be more markedly strengthened in the B0 dwarfs, shows just such a strengthening in this group of stars.

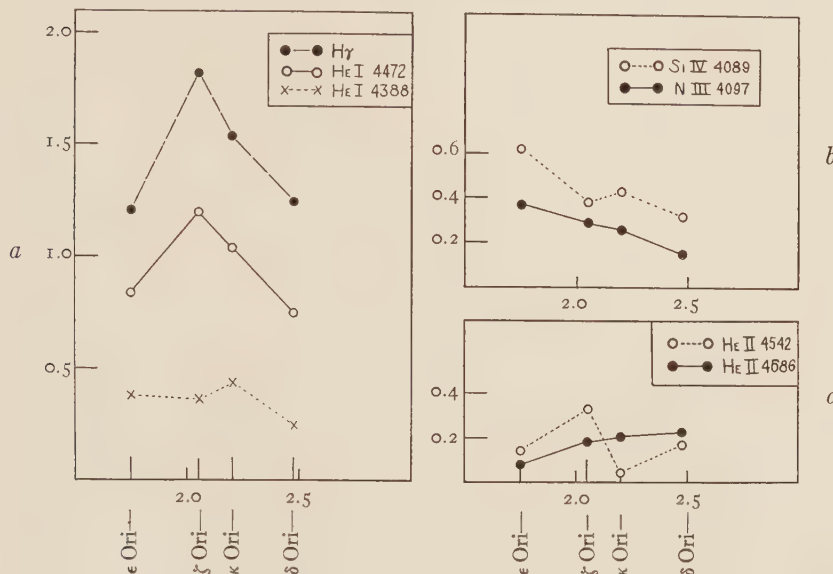


FIG. 6.—Measured intensities of various lines plotted against apparent magnitudes (abscissae) for bright stars of type B0 in Orion. Ordinates are angstroms total absorption.

In Figures 7–9, inclusive, the intensities of three singlet and three triplet lines of helium have been plotted for individual stars against the measured intensity of $H\gamma$. Each figure covers one or two Harvard subtypes, depending on the number of stars measured in each class. Thus, in each graph, the giants will be at the left, having lower hydrogen intensities. In the O stars, all the lines except perhaps $\lambda 4472$ show definite correlation of hydrogen and helium intensities, even without the isolated right-hand point (Bond 640), for which the hydrogen intensity is somewhat uncertain.

At type B0, all of the strong, well-measured lines, of both singlet and triplet systems, show the correlation mentioned above, indicating that helium lines, as well as those of hydrogen, are stronger in dwarf stars. The same is true, though less marked, in types B1 and

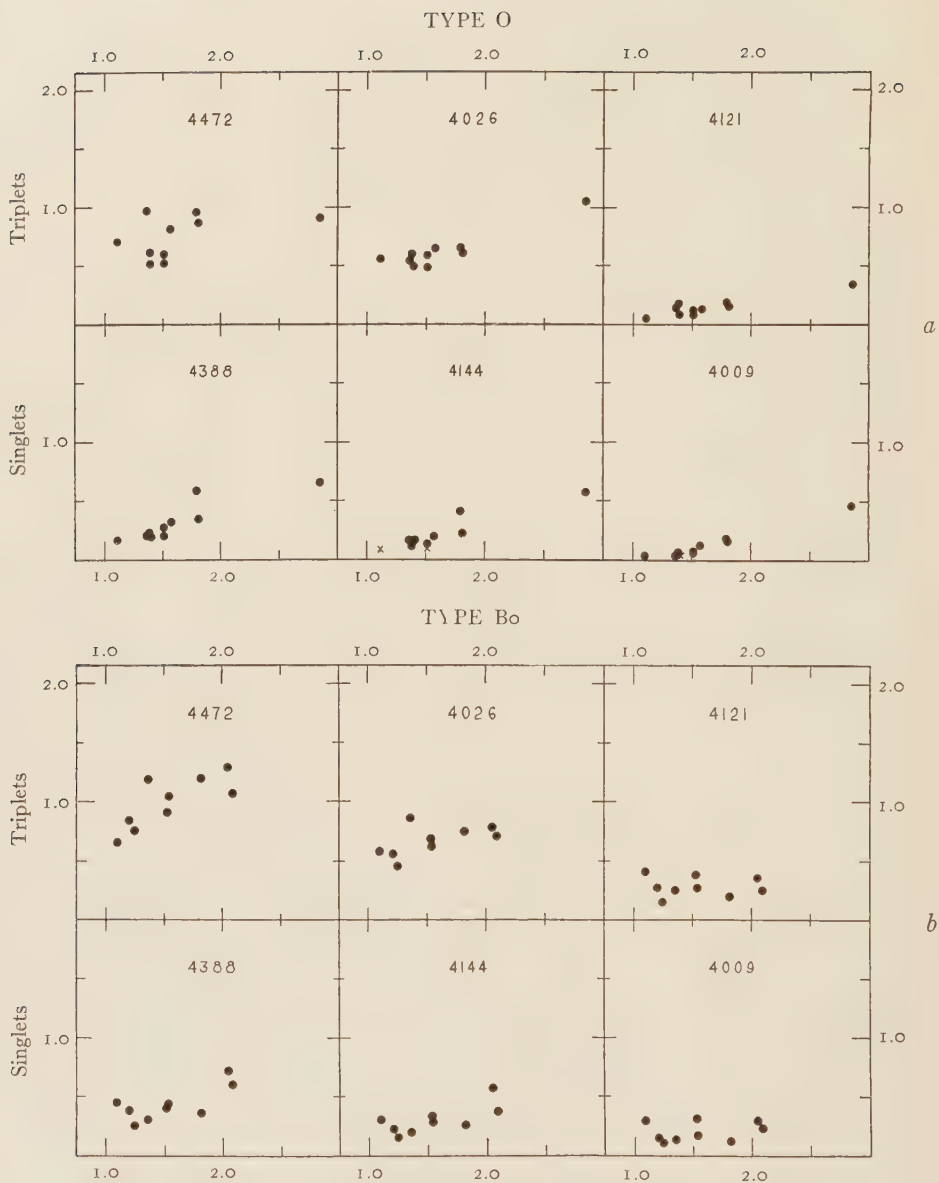


FIG. 7.—Intensities of various helium lines (ordinates) plotted against intensities of $H\gamma$ (abscissae) for stars of type O (a) and type Bo (b). All values are angstroms total absorption.

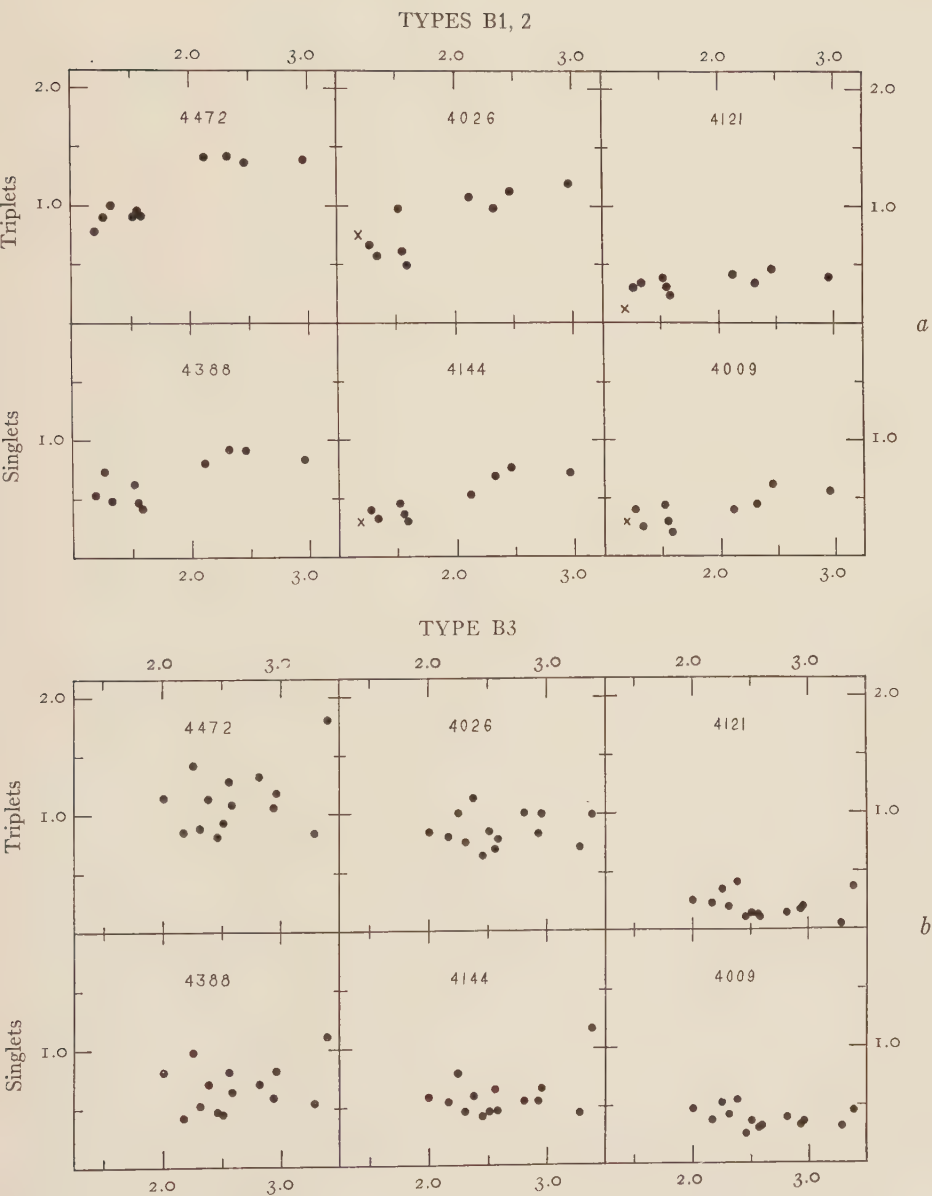


FIG. 8.—Intensities of various helium lines (ordinates) plotted against intensities of $H\gamma$ (abscissae) for stars of types B1, 2 (a) and type B3 (b). Intensities are in angstroms total absorption.

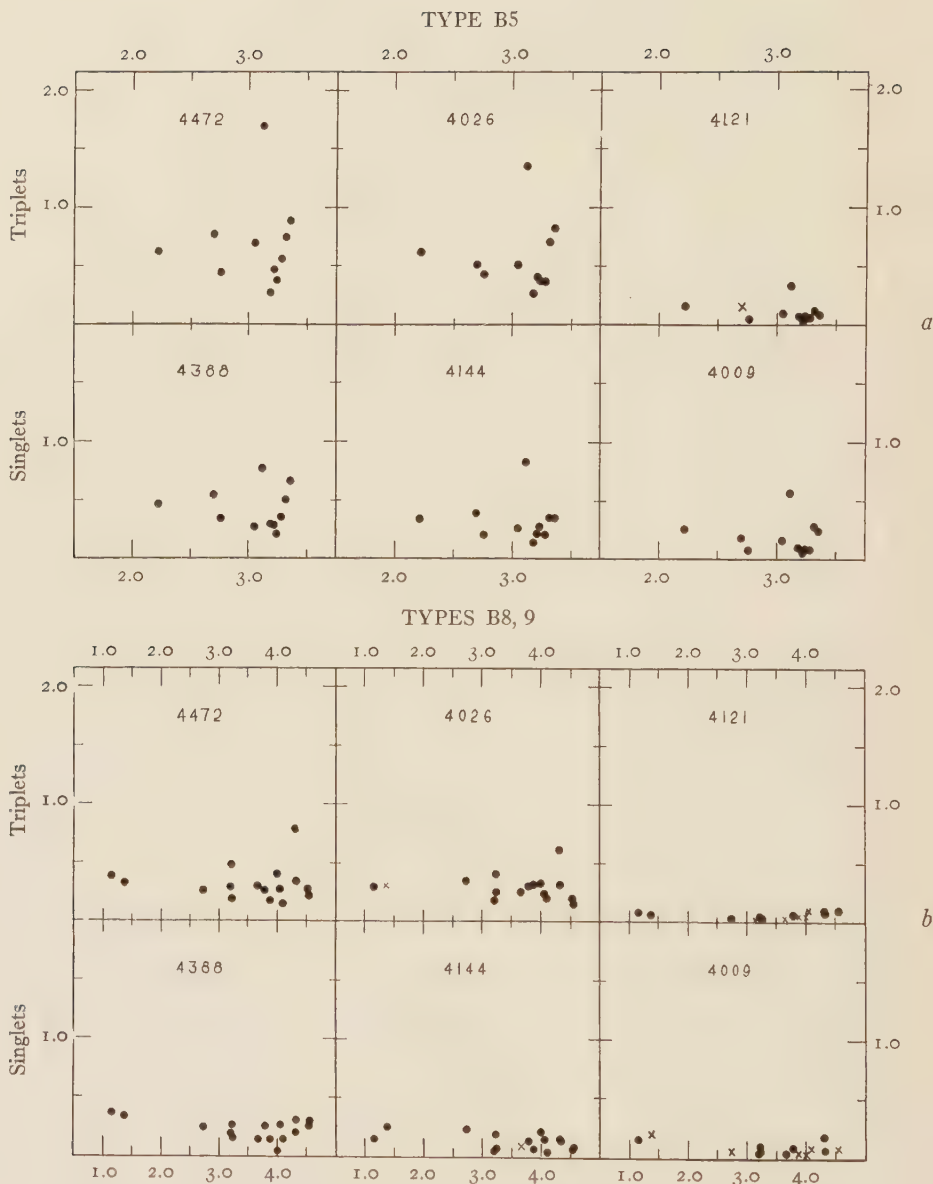


FIG. 9.—Intensities of various helium lines (ordinates) plotted against intensities of $H\gamma$ (abscissae) for stars of type B5 (*a*) and types B8, 9 (*b*). Intensities are in angstroms total absorption.

B₂.²⁴ At B₃, where none of the stars measured was called a giant, there is no appreciable correlation whatever. The graphs for type B₅ and for types B₈ and B₉ show for some lines a suggestion of the opposite effect from that shown in the groups earlier than B₃,²⁵ but the intensities are so small that the apparent effect may be due to errors of measurement.

The behavior with changing Harvard spectral type of the helium lines in the sharp-line (class I) and wide-line (class II) stars is shown in Figure 10. There appears to be no sensible difference between singlets and triplets. All curves for class I appear normal (cf. Fig. 4), but those for class II are quite definitely different, showing broad maxima more than a whole subtype later than the sharp-line stars. This suggests that in the Harvard system the rotation stars are systematically classified too late, if we take helium intensities for the criterion of spectral type. It has already been proved that, if hydrogen intensities are used as the criterion, there is no such effect. The shift of maximum is still definitely present, though of course diminished, if the peculiar B₅ wide-line star 27 Canis Majoris is entirely omitted from the discussion. The plate measured for this star, however, is well guided and of good quality. For the stronger singlet lines, indeed, one may disregard the points for class B₅ entirely, and there still remains a very definite shift of the maximum.

When Victoria subtypes are once more substituted for Harvard, as was done for the hydrogen intensities, retaining the division into classes I and II as before, the results are as shown in Figure 11. The non-rotating stars again show maximum intensities at B₂, while for the class II stars the maximum is definitely shifted to B₃.

Not enough of the seventy stars measured for this investigation have been measured by the workers at Mount Wilson to attempt a comparison on the basis of their classification.

²⁴ Miss Payne *et al.* found the same effect in the stars of the Scorpio-Centaurus cluster (*Harvard Circ.*, No. 365, 1931).

²⁵ Miss Payne *et al.* believed such an enhancement of *He I* in the giants to be present in the Scorpio-Centaurus cluster (*ibid.*).

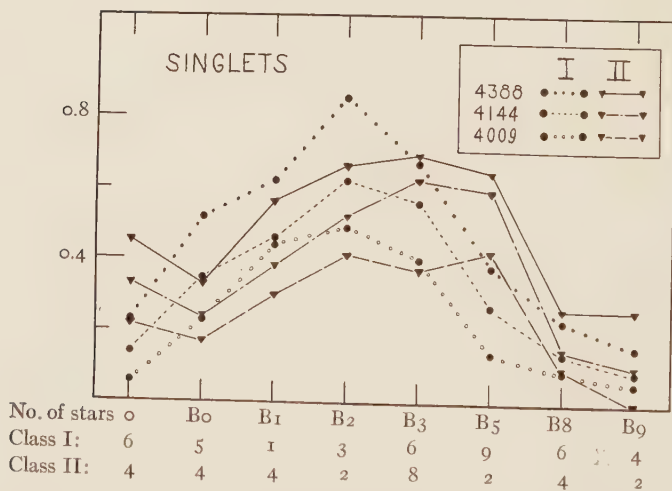
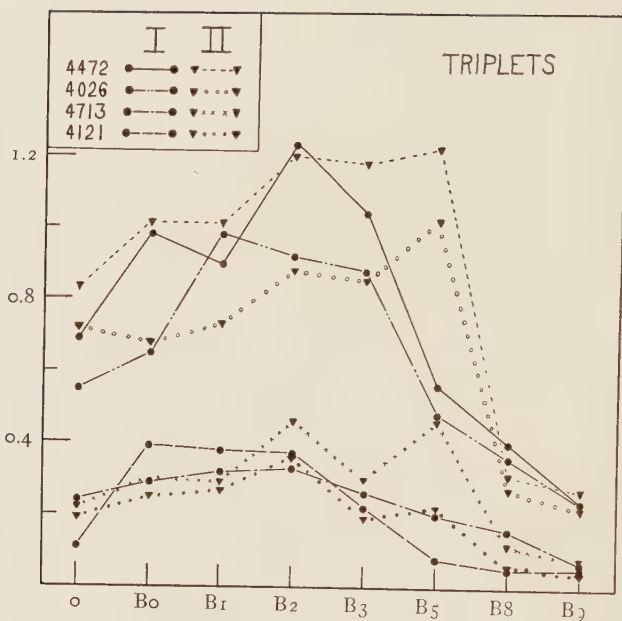


FIG. 10.—Behavior of neutral helium intensities with Harvard spectral type, in sharp-line (class I) and wide-line (class II) stars. Ordinates are angstroms total absorption.

V. BEHAVIOR OF OTHER ELEMENTS

The behavior with Harvard spectral type of such other elements as were measured in an appreciable number of stars (i.e., elements besides *H* and *He* I) is shown in Figure 12. Each point represents the mean for all stars studied in that spectral type; absences were counted as zero intensities in taking these means. Only when a line had

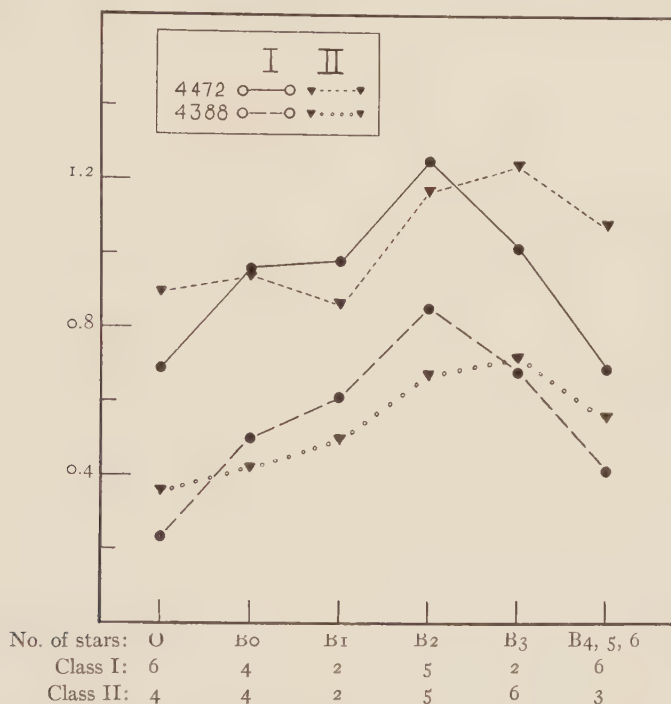


FIG. 11.—Behavior of strong helium lines with Victoria spectral type, in sharp-line (class I) and wide-line (class II) stars. Intensities are in angstroms total absorption.

been measured on the majority of plates of one Harvard subtype was its absence determined or its intensity estimated visually in the rest of the group and the mean intensity plotted in Figure 12.

The agreement with previous results, based in great part on estimated data, is excellent; there are only a few minor exceptions. Comparing with Miss Payne's data,²⁶ we find substantiated the excellent

²⁶ *M.N.*, 92, 368, 1932; see also *Harvard Circ.*, No. 256, 1924. For special reference to O stars, see H. H. Plaskett, *Pub. Dom. A p. Obs.*, 1, No. 30, 1922.

correlation which she shows between spectral type of maximum intensity and ionization potential for the various atoms and ions; there are, however, disagreements of one Harvard subclass as to the position of maximum for *N* III, *Si* IV, and *C* II. The first two of these may be due to the fact that I have considered all of the O stars measured as one group. The maximum found from my measures at type B8 for *Si* II may be spurious, owing to luminosity effects;

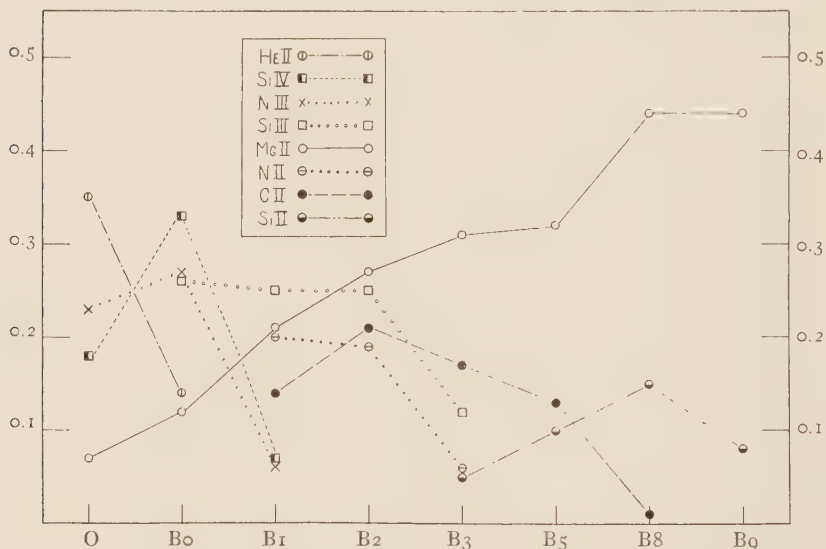


FIG. 12.—Behavior of line intensities of various elements (expressed in angstroms total absorption) with Harvard spectral type. Points shown are means for the following lines: *He* II, $\lambda\lambda$ 4200, 4542, and 4686; *Si* IV, $\lambda\lambda$ 4089, 4116; *N* III, λ 4097; *Si* III, $\lambda\lambda$ 4552, 4567, 4574; *Mg* II, λ 4481; *N* II, λ 3995; *C* II, λ 4267; *Si* II, $\lambda\lambda$ 4128, 4131.

there are three giants, in which these lines are enhanced, in the B8 group, and none in B9. Measures of spectra of types A0 and A2 will be needed to settle this point.

One is impressed, upon considering the implications of Figure 12, with the large change in spectrum corresponding to an interval of one subtype in the range earlier than B2, compared with the later classes. Compare, for instance, the breadth of the maximum for *C* II with the sharpness of the peaks for *Si* IV and *N* III.

A study of these elements, with the stars divided into giant and

dwarf groups, yields several interesting results, shown in Figure 13. $\lambda 4481$ of $Mg II$ shows no appreciable effect until B_2 , agreeing with Morgan;²⁷ in the giants of types B_8 and B_5 it is about 40 per cent

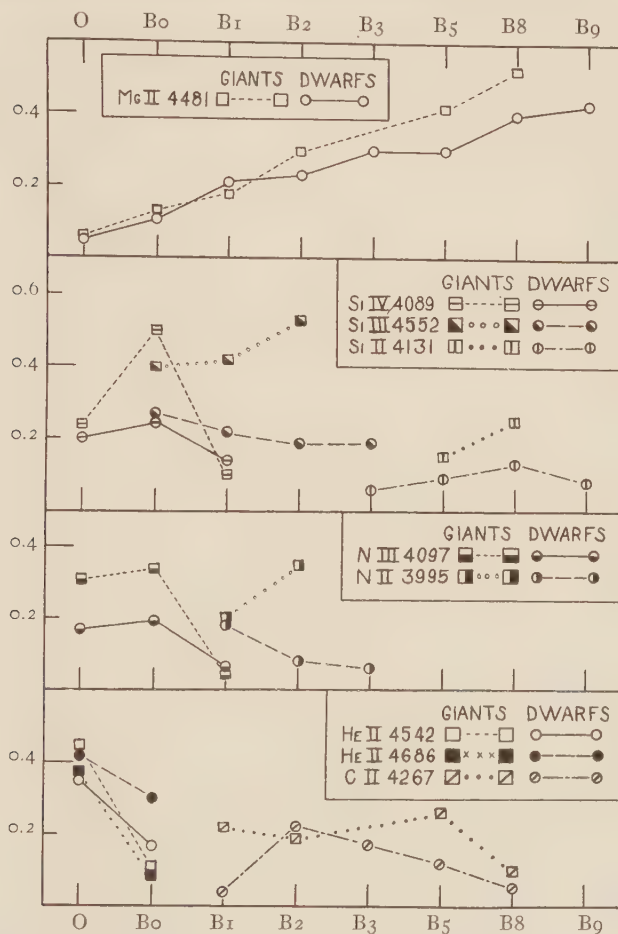


FIG. 13.—Behavior with spectral type, in giant and dwarf groups of stars, of line intensities of (a) magnesium, (b) silicon, (c) nitrogen, and (d) ionized helium and carbon.

stronger than in the dwarfs.²⁸ The ratio $\lambda 4481:\lambda 4472$, often used for a criterion of spectral type, will therefore show an absolute-magnitude effect, since one line or the other is sensitive to absolute mag-

²⁷ *A p. J.*, 77, 291, 1933.

²⁸ This strengthening was noticed by Struve (*ibid.*, 78, 82, 1933).

nitude in every subdivision of the B stars. Every one of the measured lines of silicon and nitrogen in various stages of ionization shows approximately twice the maximum strength in giants that it shows in dwarfs. $C\ II$ also is enhanced in the B₅ and B₈ giants.

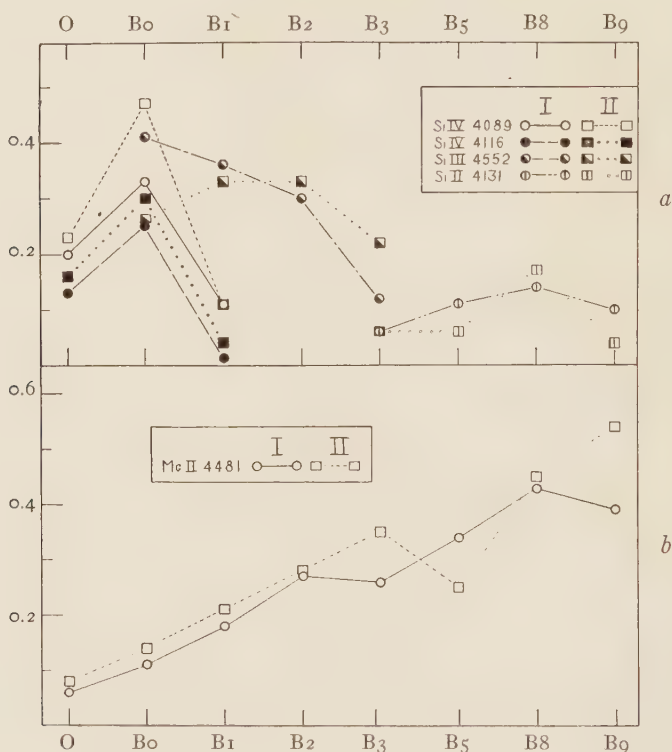


FIG. 14.—Behavior with Harvard spectral type of line intensities of (a) silicon and (b) magnesium, in stars with sharp lines (class I) and with wide lines (class II). Ordinates are angstroms total absorption.

Thus, the spectra of $He\ I$ (in the types earlier than B₃) and of hydrogen remain the only ones in which the lines are consistently more intense in dwarfs than in giant stars.

The behavior of ionized helium should be mentioned in this connection. Referring to Figure 13 (d), we see that the mean intensities of $\lambda\ 4686$ and $\lambda\ 4542$ (members of different series) are not greatly different in the giants and dwarfs of type O, but at B₀ they are

stronger in the dwarfs. This effect is more marked in λ 4686, with the result that this line is three times as strong in B0 dwarfs as in giants, while λ 4542 is only 50 per cent strengthened in the dwarf group. The noteworthy feature of this effect is that the B0 stars in Orion, as mentioned in section IV, show the same thing; that is, λ 4686 is more intense in the fainter and presumably less luminous of those stars, while λ 4542 shows no definite correlation.

Upon investigating the effects of rotation (Fig. 14), we find that nearly all of these elements show no systematic effect (e.g., *Si* II, *Mg* II); λ 4089 of *Si* IV, however, is apparently definitely stronger in the rotating stars (class II) at B0. No obvious explanation suggests itself; λ 4116, also due to *Si* IV, shows the effect only to an extent well within the errors of measurement. *Si* III also seems to be stronger in the class II stars at B0, though not in the later types.

I wish to express my sincere thanks to Dr. Otto Struve and to Dr. W. W. Morgan for suggesting this problem and for their frequent and helpful advice, and to Dr. H. Rosenberg for his kindness in allowing me to use his photometer.

YERKES OBSERVATORY
WILLIAMS BAY, WISCONSIN
December 28, 1935

